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Maritime Platforms Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

This paper presents the results of a trial to measure the acceleration, pressure loading and displacement of a fixed flat steel plate subjected to explosive blast loading.

It is concluded that neither the Fagel formula or simple FEM simulation give accurate predictions of acceleration for a fully clamped square plate subject to a short duration explosive blast loading. The FEM predictive capability may be improved with more accurate materials information plus a more refined model.

This experiment has produced results which can be used to refine the Finite Element models of ship decks, subject to explosive blast loading, to predict acceleration.

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Executive Summary

Injury to personnel on a ship due to blast from munitions is generally thought to be the result of the blast wave or fragments striking the body.

A cause of injury, so far little studied, is the effect of the rapid acceleration of the deck, or deck mounted equipment, on the human body caused by munitions exploding on a lower deck. This acceleration can cause both short and long term injury. Any injury that removes personnel from action lowers the overall chance of success of the mission.

This experimental series is the first stage of a program to quantify the acceleration loads on the lower limbs and/or torso of personnel on a deck subject to blast loading from below.

This report describes a series of trials to measure the acceleration and displacement of a square steel plate subject to explosive loading, and reports the results of those measurements.

The results of this experiment will be used to validate future finite element models of a ship deck with personnel and equipment placed on the deck. This will ultimately lead to the ability to predict casualties by modelling the explosion of a munition anywhere in or near a ship structure.

When data becomes available on criteria for lower limb injury (from work currently being carried out by Weapons Systems Division) it will be possible to predict the type and severity of injury from the acceleration of an explosively loaded deck plate.

Contents

1. Introduction

Injury to personnel on a ship due to detonation of munitions is the result of a combination of effects of the explosive shock front impacting the body, and damage from munition fragments and debris produced by the blast, striking the body.

A blast event causes two distinct accelerations in adjacent structure and personnel. The first is characterised by very high acceleration levels, accompanied by only small displacements. The second is characterised by a much lower level of acceleration with a larger displacement. This second acceleration regimè is similar to that experienced in a car crash, which has been the subject of extensive injury studies. So far little studied, is the effect of the very high acceleration regimè on the human body.

This acceleration can cause limb injuries [1] ranging from nerve damage, soft tissue injury and internal bleeding, right up to broken or shattered bones, crushed cartilage, torn ligaments, compound fractures, ie. bone protruding through the skin, and finally to completely "pulped" limbs. It can also produce mild to severe spinal injury in a person seated on a rigid framed chair. All these injuries are due to the passage of the shock front through the body, at a rate greater than that at which the body can absorb the energy.

This experimental series is the first stage of a program to quantify the acceleration loads on the lower limbs of personnel standing on, and/or the torso of personnel sitting on, furniture mounted on a deck subject to blast from below

This report describes a series of trials intended to measure the acceleration and displacement of a fixed lm square steel plate subject to explosive loading, and reports the results of those measurements.

The results of this experiment will be used, in the future, to validate finite element models of this experimental setup, enabling the correct material parameters to be established for typical ship structural components. These parameterised materials will then be used to model a ship deck, with personnel and equipment placed on the deck in a layout similar to an existing ship. This model will then be subject to a simulated blast from below, simulating an explosion of a munition between the decks of a ship.

When data becomes available (from work currently being carried out in Weapons Systems Division) on criteria for lower limb injury, it will be possible to predict the type and severity of injury from explosively loaded deck plate acceleration.

2. Experimental Description

2.1 Mechanical

A series of 1200 mm square, 5 mm thick mild steel plates (AS3678-250) were bolted to a heavy steel frame with 24 high tensile bolts, tensioned to 11.06 N.m. This left a central area approximately 1000 mm square free to move under load. The frame was positioned on four Pendine blocks. Space was available between the blocks for access to the bolts and also to position the instrumentation, as can be seen Figure 1.

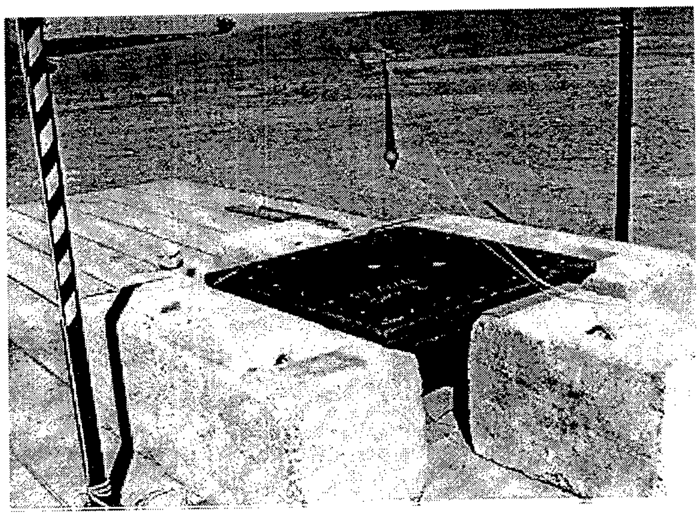


Figure 1 General experimental arrangement

2.2 Instrumentation

Each plate had five gauges mounted on it. There were two Endevco 7255A piezoelectric accelerometers, two PCB Piezotronic 109A piezoelectric pressure gauges, and a Novotechnik TI50 LVDT resistive displacement gauge. The gauges were arranged on the plate as shown in Figure 2.

The accelerometers were mounted on an AMRL-designed triangular aluminium mount [2]. The gauges have a range of 0-50000 *g* and a frequency response of 0-10 kHz.

The pressure gauges were mounted in a nylon holder which then screwed into a steel adapter welded into the plate. This mounting system is designed to isolate the gauge from forces parallel to the plate surface. The top of the gauge was smeared with silicone grease then covered with thin reflective tape to insulate the gauge from radiant heat from the explosion. These gauges have a range of 0-690 MPa and a rise time of 1μs.

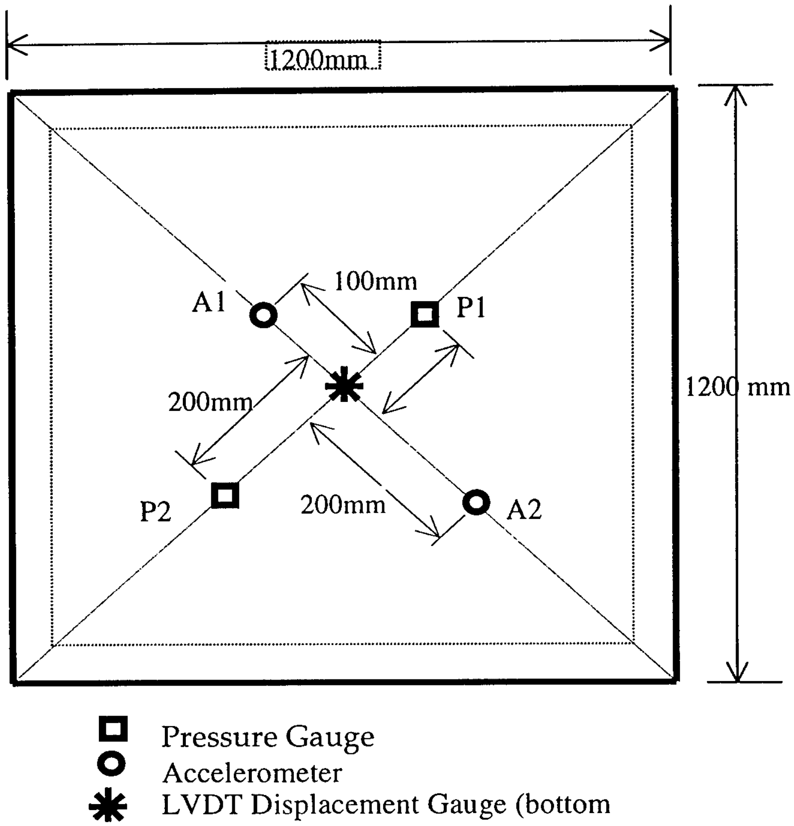


Figure 2 Instrument Location

The displacement gauge had a 150 mm range, in this case utilised as ±75 mm. It was mounted to a free-standing frame positioned under the centre of the plate. The base of the frame sat on a block of wood positioned on top of a sand bag. This allowed simple adjustment of the initial vertical alignment of the gauge, and also minimised the possibility of damage to the gauge if the plate exhibited large lateral movements. The top of the gauge was attached to an adapter which bolted through the plate. The adapter was to be sacrificial in case of damage from the explosive products, thus protecting the gauge end screw.

All the instrument readings were recorded using Digistar III high speed electronic data recorders. The Digistars recorders were triggered by a pulse coincident with the firing pulse. Time of arrival (TOA) of the shock front was calculated using the trigger point of the record time base.

2.3 Explosive

In all four shots, a sphere of Pentolite weighing 250 g was detonated centrally using an Exploding Bridge Wire detonator. The plate to explosive standoff distance varied from 250 mm to 500 mm.

2.4 Predicted Results

Prior to testing, an estimate was made of the expected peak overpressure and accelerations. These values were used in gauge selection and the setting of the instrumentation ranges. CONWEP[3] was used to model the pressures, and Finite Element Modelling using LD-DYNA3D and theoretical analysis were employed to estimate the accelerations.

2.4.1 CONWEP

Table 1 details the standoff distance, expected overpressure readings, positive impulse and time of arrival (TOA) of the pressure front for pressure gauges P1 and P2, calculated using the CONWEP program.

Table 1 Predicted overpressure and TOA

Gauge		PI			P2		
Event	Standoff (mm)	Peak Overpressure (MPa)	Positive Impulse (kPa.s)	TOA (μs)	Peak Overpressure (MPa)	Positive Impulse (kPa.s)	TOA (μs)
E14 and E15	500	10.8	0.54	215	9.3	0.50	237
E16	400	18.7	0.72	147	15.2	0.65	170
E17	250	48.0	1.34	72	33.7	1.05	96

2.4.2 LS-DYNA3D

An initial estimate of the displacement and acceleration was attempted using the LS-DYNA3D[4] Finite Element Analysis code. The plate was modelled with isotropic elastic/plastic shell elements. The material characteristics of the model are shown in Table 2. The input pressure waveform used was planar, ie. the pressure was applied equally over the plate, with values derived from CONWEP, as shown in Table 1. The accelerometers and pressure gauges were modelled as lumped masses at the correct location.

Table 2 FEM Material Characteristics

Property	Value
Young's Modulus, E	203 GPa
Poissons Ratio, ν	0.3
Yield Stress, σ_0	270 MPa
Tangent Modulus, E_T	470 MPa
Density, ρ	7850 kg/m^3
Hardening Parameter, β	1.0

The predicted values, shown in Table 3, were based on static material properties for the steel used, ie. no account was taken of strain rate effects.

Table 3 Predicted acceleration and displacement

Event	Predicted Acceleration A1 (g)	Predicted Acceleration A2 (g)	Predicted Displacement D1 (mm)
E14 and E15	18960	18960	35
E16	30185	30185	44
E17	67100	56000	74

2.4.3 Theoretical

Using a formula from Fagel[5] , acceleration at the centre of a flat plate using a single degree of freedom theoretical model can be calculated from

$$Acceleration = 1.5 \times \frac{Peak\_Overpressure}{Mass/Unit\_Area} \quad \mathrm{m/s^2}$$

Using the predicted peak overpressure from Table 1 and a mass/area of 39.25 kg/m^2, this formula gives the accelerations shown in Table 4. Since these figures are the prediction at the centre of the plate, and the accelerometers are off-centre, then some difference can be expected.

Table 4 Theoretical Centre Plate Accelerations

Event	Predicted Acceleration (m/s^2)	Predicted Acceleration (g)
E14 and E15	42,116	4297
E16	72932	7443
E17	187182	19100

This model does not include the masses of the gauges, which in any case would have no significant effect on the acceleration response.
These acceleration figures are based on a model which includes all frequency response modes. However, the gauges used have a best frequency response of 10kHz. Since this lower frequency response would reduce the peak measured value, then it was expected that the measured accelerations would be within the capabilities of the gauge.

3. Results and Discussion

Figures 3-7 show the Digistar recorded traces for each of the instruments for each of the events.

As has been observed in other trials, it is very difficult to make pressure and acceleration measurements on a flat steel plate subjected to severe dynamic loading from close proximity charges. The difficulty is in the "ringing" of the pressure gauge due to pressure effects transmitted through the plate.

The traces from the pressure transducers exhibit a large amount of noise, making determination of the initiation time, and hence TOA, and peak overpressure problematical. A frequency analysis of the data, using the DATAK computer program [6] showed no obvious noise frequencies, meaning that filtering would not help. Two approximating curve fits were made to each pressure trace using Datack which implements a procedure outlined by Slater [7]. A straight line is fitted to the rising edge of the pressure wave, and an exponential curve to the decaying portion of the signal. This allows a reasonable approximation to be made to the pressure wave trace and gives an approximate peak overpressure, positive impulse and TOA. These approximate figures, plus the measured peak acceleration and displacements, are shown in Tables 5 and 6.

Table 5 Measured Acceleration and Displacements

Gauge	A1	A2	D1	
Event	Peak Accel (g)	Peak Accel (g)	Peak Displ. (mm)	Permanent Displ. (mm)
E14	14657	14748	-33	-4
E15	13185	14239	-33	-4
E16	17529	15052	-36	-6
E17	40969	30049	-35	-9

Table 6 Estimated Overpressure, Positive Impulse and Time Of Arrival

Gauge	P1			P2		
Event	Approx Peak Overpressure (MPa)	Positive Impulse (kPa.s)	Approx TOA (μs)	Approx Peak Overpressure (MPa)	Positive Impulse (kPa.s)	Approx TOA (μs)
E14	9.4	0.44	246	8.7	0.38	249
E15	9.4	0.38	239	8.0	0.33	237
E16	16.4	0.36	171	16.4	0.47	176
E17	40.0	1.02	100	37.5	0.76	108

The measured peak accelerations, shown in Table 5, were higher than the predictions, shown in Tables 3 and 4, in all cases. This could be due to inaccuracies in the measurement or alternatively to deficiencies in the predictive models. There was no clipping of the signal, showing that the different value was not due to range setting error. As mentioned previously, the 10kHz gauge frequency limit may have influenced the value, as the overpressure has peaked and largely dissipated by 100μs, the rise time of the gauge. This may lead to doubts that any high frequency accelerations can be measured with these gauges. Since the FEM models were based on estimated characteristics then it is possible that the estimates were wrong, leading to the discrepancy. There was also no refinement of the FEM models, which could have improved the accuracy of the prediction.

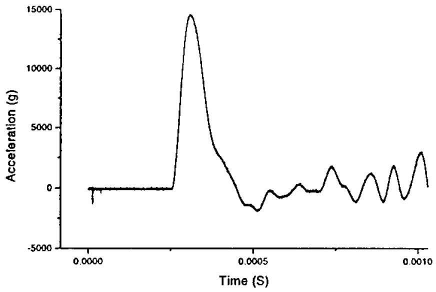
The peak pressures estimated from the curve fits coincided reasonably well with the expected figures. There is some room for adjustment of the estimated pressures depending on the location of the fitted curve obtained. The estimated impulse, Table 6, is lower than predicted by CONWEP, shown in Table 1, in all events.

The TOA in all cases is later than predicted by CONWEP, cf Tables 1 and 6, however as stated earlier, the location of the trigger point is not easy to determine from the recorded traces.

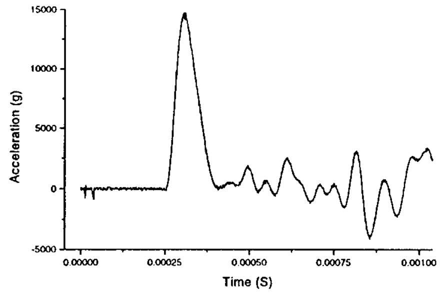
The displacement was close to the estimated value for the 500 mm standoff distance. However the predicted 400 mm and 250 mm standoff displacements are a long way from the measured values. Again this could be due to the estimates used in the predictive FEM models.

The clipping in Figure 3e was due to the incorrect setting of the initial offset of the displacement gauge, ie. the gauge was not in the mid point of its travel. This was rectified in the later events. The plate has been excited into oscillation by a very short duration loading, leading to an essentially sinusoidal wave at the plate centre. The waveform of Figure 6e shows a considerably less sinusoidal shape than the previous three events. Here higher frequency oscillations appear to overlay the fundamental frequency, due possibly to the much greater loading exciting higher frequency vibration modes.

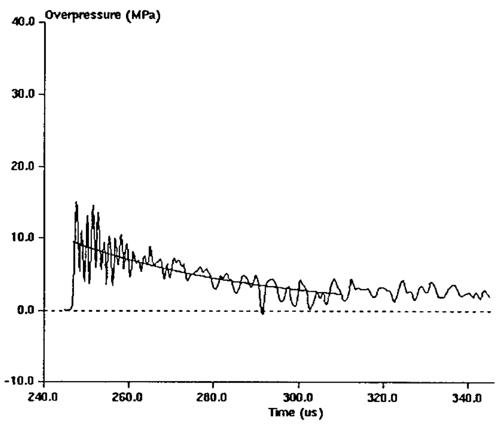
As stated earlier, the intention is to use the data gathered in this experiment to validate FEM models of ship decks. However this experimental setup may not be the optimum. The explosive loading impinges on only a small central area of the plate, whereas a larger explosive, representative of a real anti-ship weapon, would produce loading with a larger impulse impinging over a larger area, and hence a different loading regimè than was observed here. Stiffened panels, as used in ship construction, would also behave differently under load, compared with the unstiffened plate used in this case. If funding allowed, an actual deck section or manufactured replica, loaded by a typical anti-ship weapon would give much more representative results. Alternatively, a decommissioned RAN ship could be instrumented under trial conditions, as occurred with the Ship Survivability Enhancement Program in 1994.



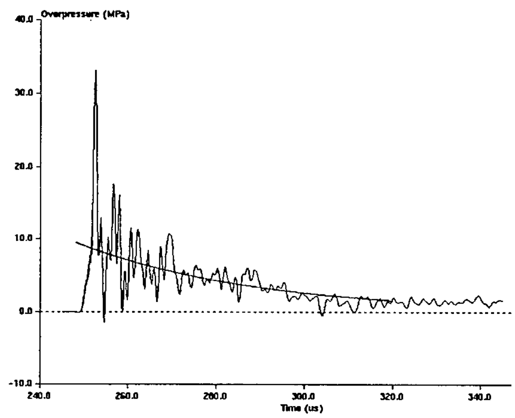
a) Accelerometer A1



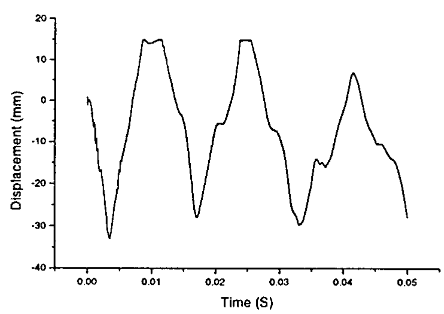
b) Accelerometer A2



c) Overpressure P1

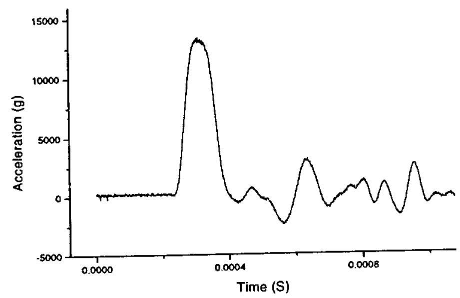


d) Overpressure P2



d) Displacement D1

Figure 3   Results from Event E14   Standoff 500mm



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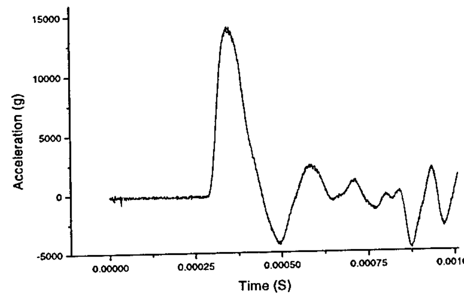
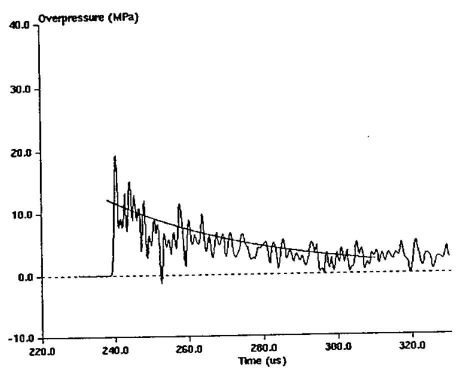


b) Accelerometer A2



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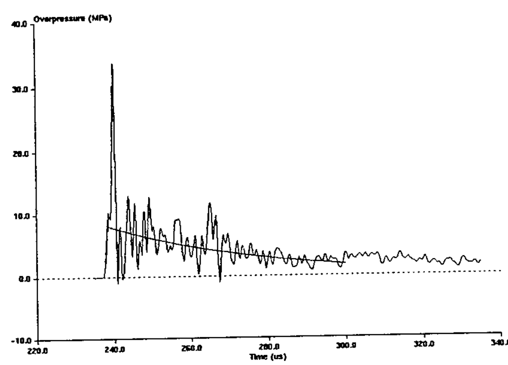
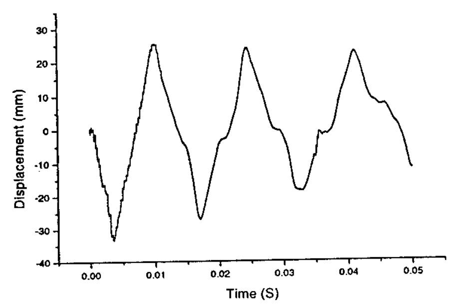
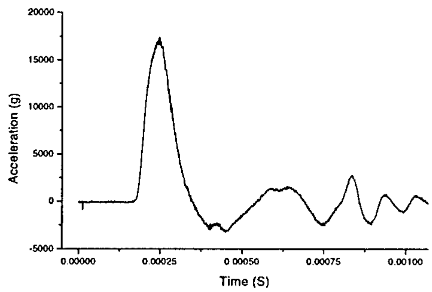


d) Overpressure P2



e) Displacement D1

Figure 4 Results from Event E15 Standoff 500mm



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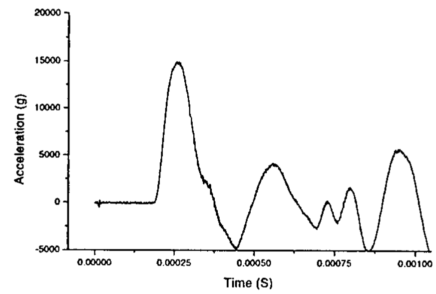
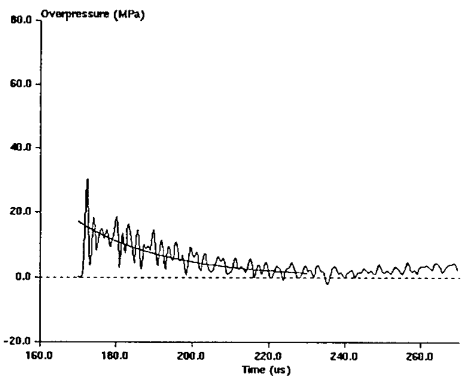
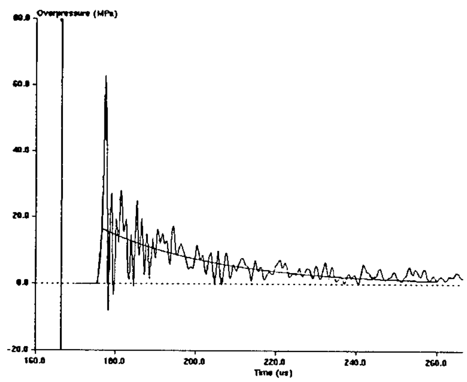


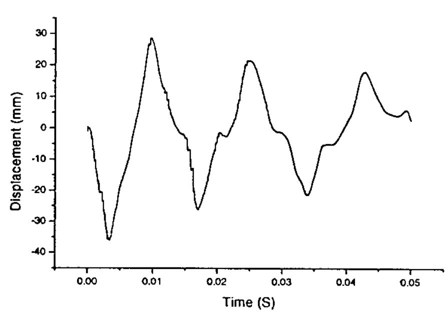
b) Accelerometer A2



c) Overpressure P1

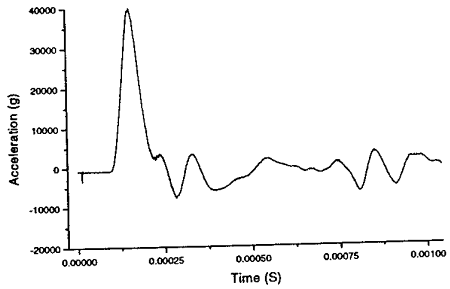


d) Overpressure P2

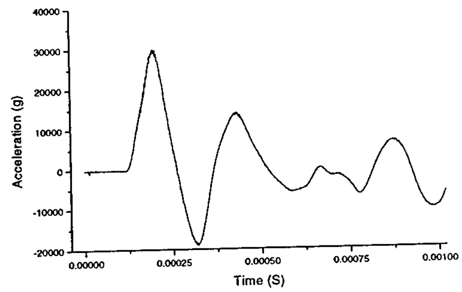


e *) Displacement D1*

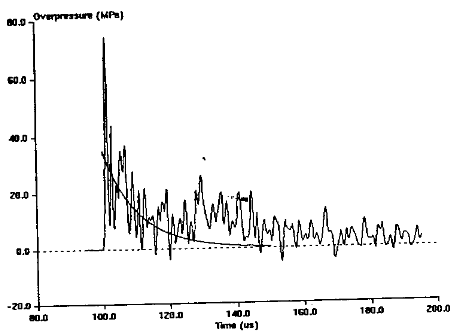
Figure 5 Results from Event E16 Standoff 400mm



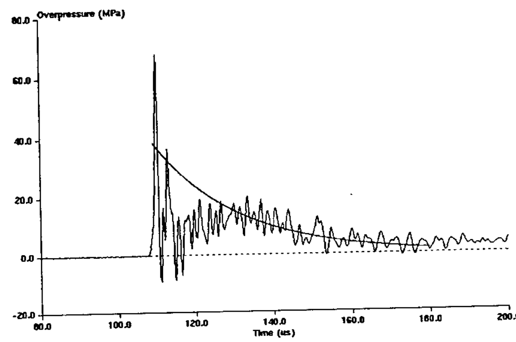
a) Accelerometer A1



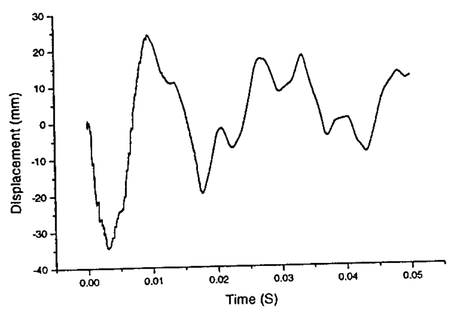
b) Accelerometer A2



c) Overpressure P1



d) Overpressure P2



e) Displacement D1

Figure 6 Results from Event E17 Standoff 250mm

4. Conclusion

It is clear that neither the Fagel formula or a simple FEM simulation give accurate predictions of acceleration for a fully clamped square plate subject to a short duration explosive blast loading. The FEM predictive capability may be improved with more accurate materials information plus a more refined model.

This experiment has produced results which can be used to refine the FE models of ship decks, subject to explosive blast loading, to predict acceleration.

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19. ABSTRACT

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